Heavy Neutral Lepton on Future Muon Collider

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Muon Collider Physics and Detector Workshop, Fermilab, Dec 15, 2022

Outline

- Neutrino Mass
- Heavy Neutral Leptons
- Search at Future Muon Collider
  - Muon flavor
- Various Experimental Constraints

Origin of Neutrino Mass

- In SM, neutrino is massless. While the experiments have confirmed its tiny mass smaller than O(0.1) eV.
- Effective Operator: Weinberg Operator $\dfrac{LLHH}{\Lambda}$
- Seesaw mechanism
  - Simple Type I
  - Inverse seesaw model
  - Linear seesaw model
- We choose to work in a simple scenario. Suppose there is heavy neutral lepton. We can parametrize its mass m_N
  mixing angle with SM neutrino. $U_l = \sin\theta_l$

$$\mathcal{L} = \mathcal{L}_W + \mathcal{L}_Z + \mathcal{L}_H$$

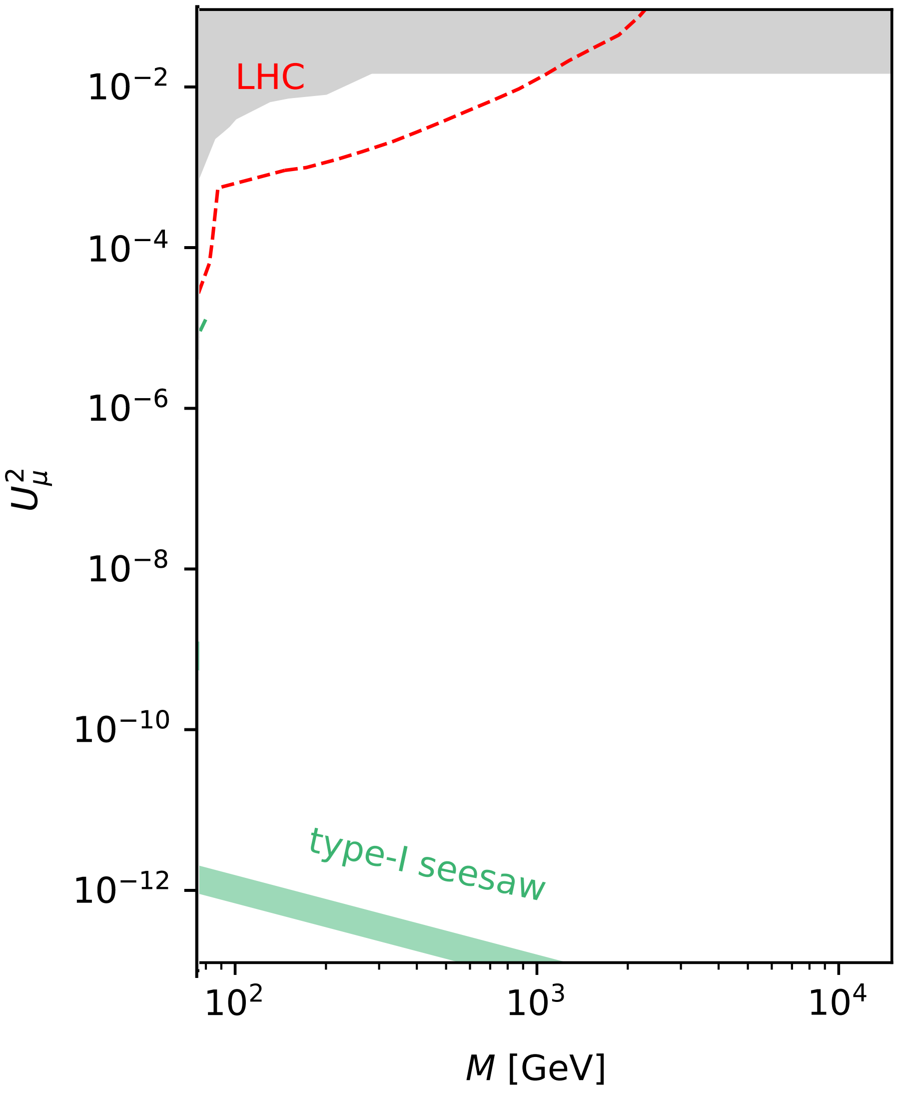
$$\mathcal{L}_W = \frac{gU_l}{\sqrt{2}}\left(W_\mu \bar{l}_L \gamma^\mu N + h.c.\right)$$

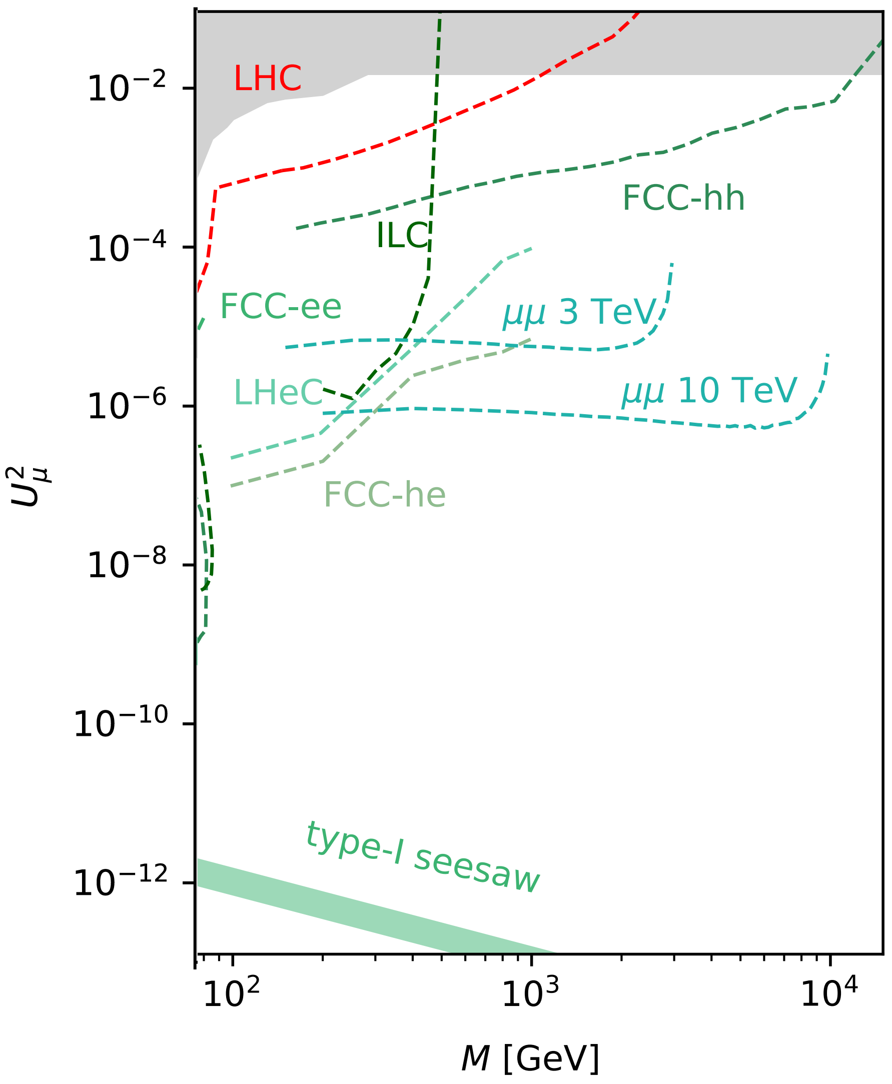
$$\mathcal{L}_Z = -\frac{gU_l}{2\cos\theta_w} Z_\mu \left(\bar{\nu}_L \gamma^\mu N + \bar{N}\gamma^\mu \bar{\nu}_L\right)$$

$$\mathcal{L}_H = -\frac{U_l m_N}{v} h\left(\bar{\nu}_L N + \bar{N}\nu_L\right)$$

Our current focus

$m_N > O(100)\mathrm{GeV}$





The muon collider can open and probe new region space in the parameter space. even compared to other future colliders!

Snowmass Energy Frontier Report: 2211.11084

Search at Muon Collider

- The future muon collider includes 3 TeV and 10 TeV scenarios.
- Clean background, fixed cms energy, excellent environment for the muon flavor HNL
- Here we show the muon-flavor Dirac HNL as benchmark.

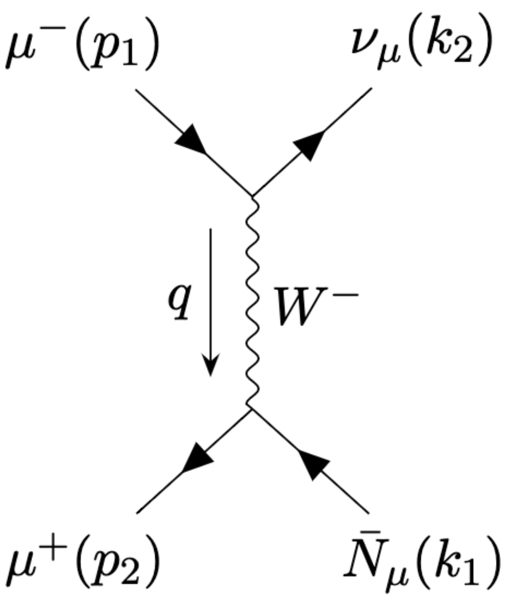
- Tools:

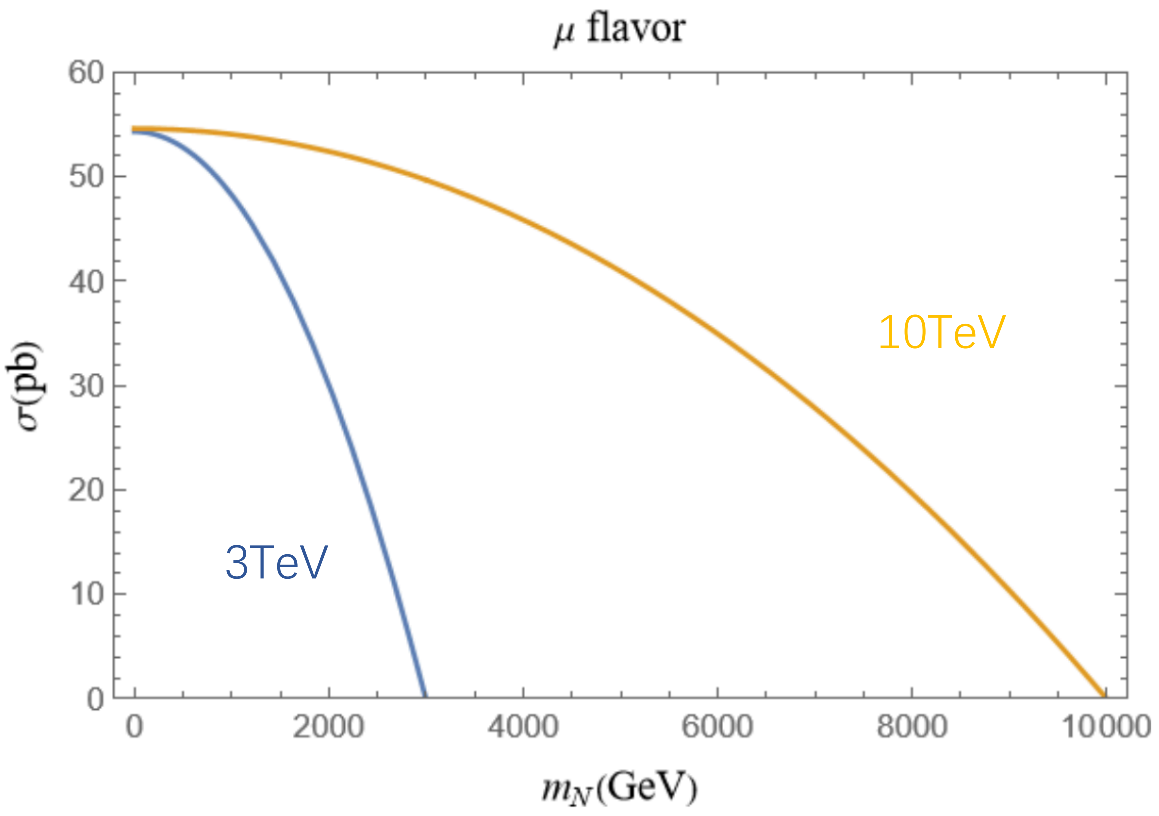
  Using MadGraph 3.4 to simulate and then make analysis
- Effective Vector-Boson Approximation (EVA) or gauge boson PDF has been implemented

Muon Flavor

- Signal: Production of N_μ
  Dominated by the t-channel

$$\mu^+ + \mu^- \to N_\mu + \bar{\nu}_\mu$$





Type	Signal process	$\sigma/U_\mu^2(m_N = 1000\text{GeV})$
t-channel	$\mu^+\mu^- \longrightarrow N_\mu\bar{\nu}_\mu$	48.26 pb
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^- N_\mu\bar{\nu}_\mu$	~ 1 pb
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu\nu_\mu N_\mu\bar{\nu}_\mu$	~ 0.1 pb

Table 1: Signal for μ flavor at 3 TeV

Decay of N_μ

HNL can promptly decay via neutral current or charged current or to the higgs. Here we select its decay channel to W boson.

$$N_\mu \to W^+ + \mu^-, W^+ \to jj$$

We assume the W boson can be well reconstructed from the two jets.

We focus on the final states W^+ and μ^- and reconstruct its invariant mass distribution.

10TeV Background

Dijets can be from either W or Z boson.

Type	Background process	σ/U_μ^2	Cut	Taking account
t-channel	$\mu^+\mu^- \longrightarrow W^+\mu^-\bar{\nu}_\mu$	0.107 pb	default cut	Yes
t-channel	$\mu^+\mu^- \longrightarrow Z\mu^+\mu^-$	0.232 pb	default cuts & missing μ^+	Yes
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^-W^+\mu^-\bar{\nu}_\mu$	0.2 pb	default cut ($\mu^+\mu^-$ are missing)	Yes
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu\nu_\mu W^+\mu^-\bar{\nu}_\mu$	0.0343 pb	default cut	No

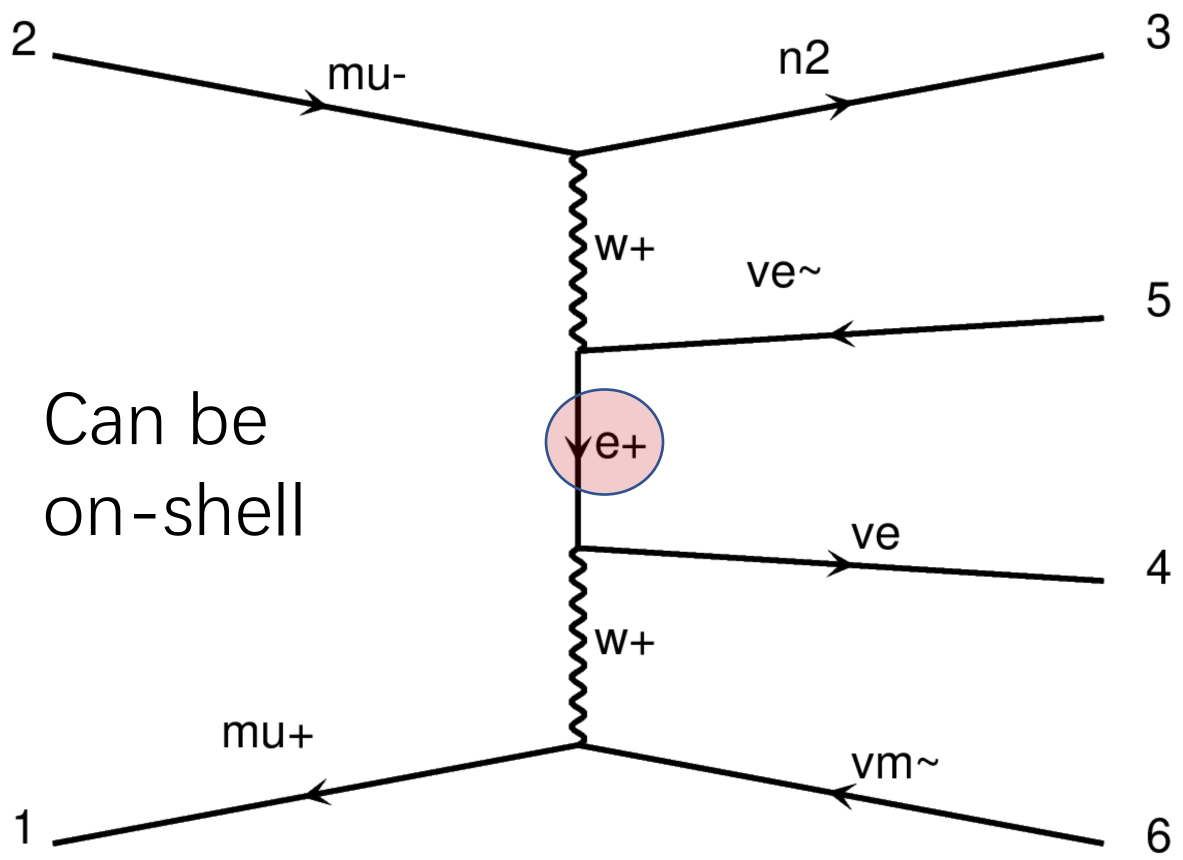
TABLE IV. Background for μ flavor at 10 TeV

Using EVA in MadGraph, especially photon PDF
VBF processes dominates at 10 TeV

Default cut:
For muon:
PT > 20GeV,
Eta < 2.5

Using EVA will lead to t-channel singularity.
So we just generate 2 -> 5 processes directly in MadGraph.

(Real) t-channel singularity



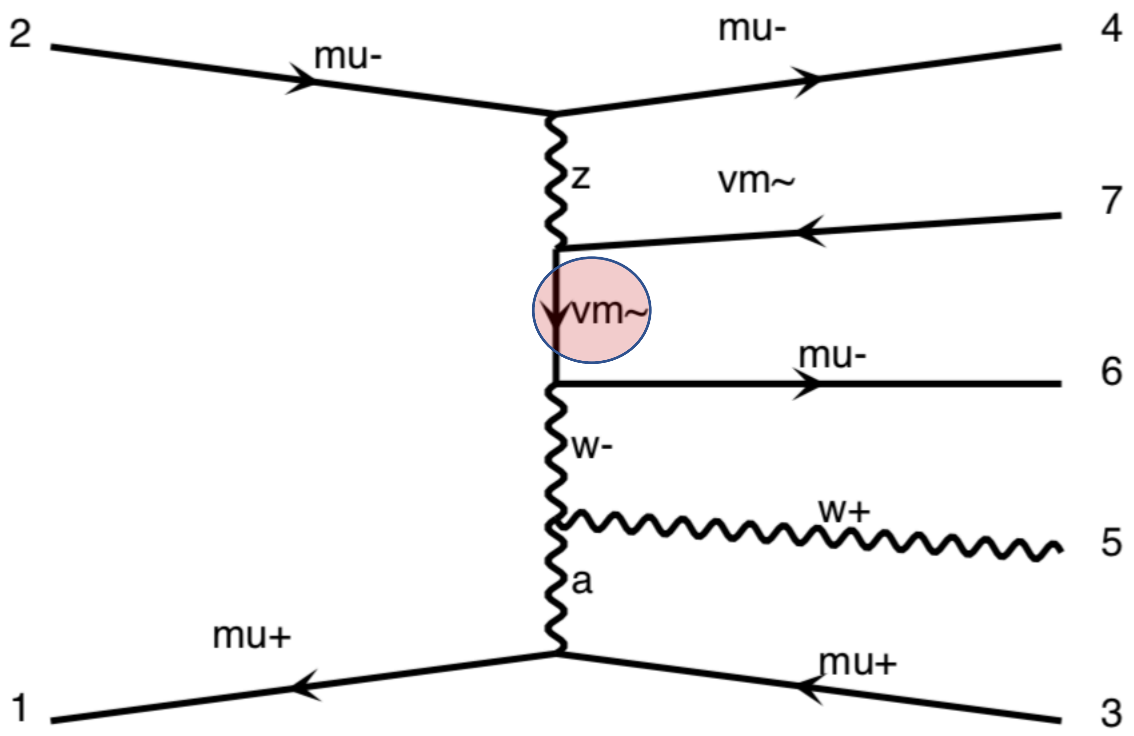
Can be
on-shell

Complex mass regulation
hep-ph/9509314

The cross section is proportional to the beam size.
hep-ph/9601290

We are trying to gain a better understanding.
(In progress)

(Fake) t-channel singularity: Subtlety of EVA



In 2 to 5 full processes, the intermediate neutrino can never be on-shell.

But in EVA, if we treat the gauge boson are "real" , the neutrino can be on-shell which induce t-channel singularity.

One plausible way is to make the light particles are from the decay of heavy gauge bosons.

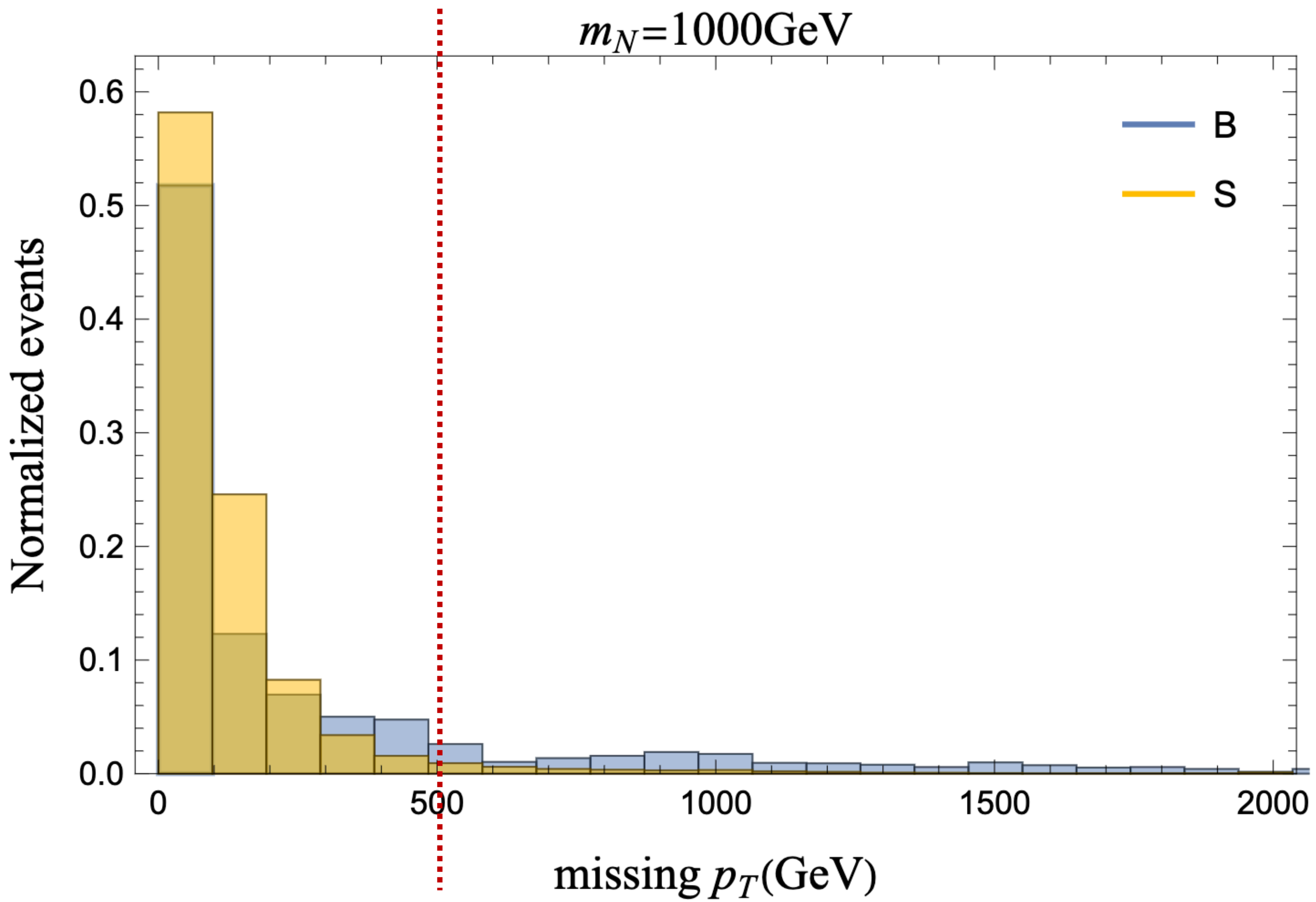
Cutflow Analysis

1. We assume the W boson can be well constructed from the dijets (Z boson can fake).
2. Combine the W^+(Z) and μ^- to try to reconstruct the HNL

Impose the mass window:
Require a cut around the heavy neutrino mass.

$$m_N < 500\mathrm{GeV}: \qquad m_N \pm 0.1 m_N$$
$$m_N \geq 500\mathrm{GeV}: \qquad m_N \pm 50\mathrm{GeV}$$

After mass window selection

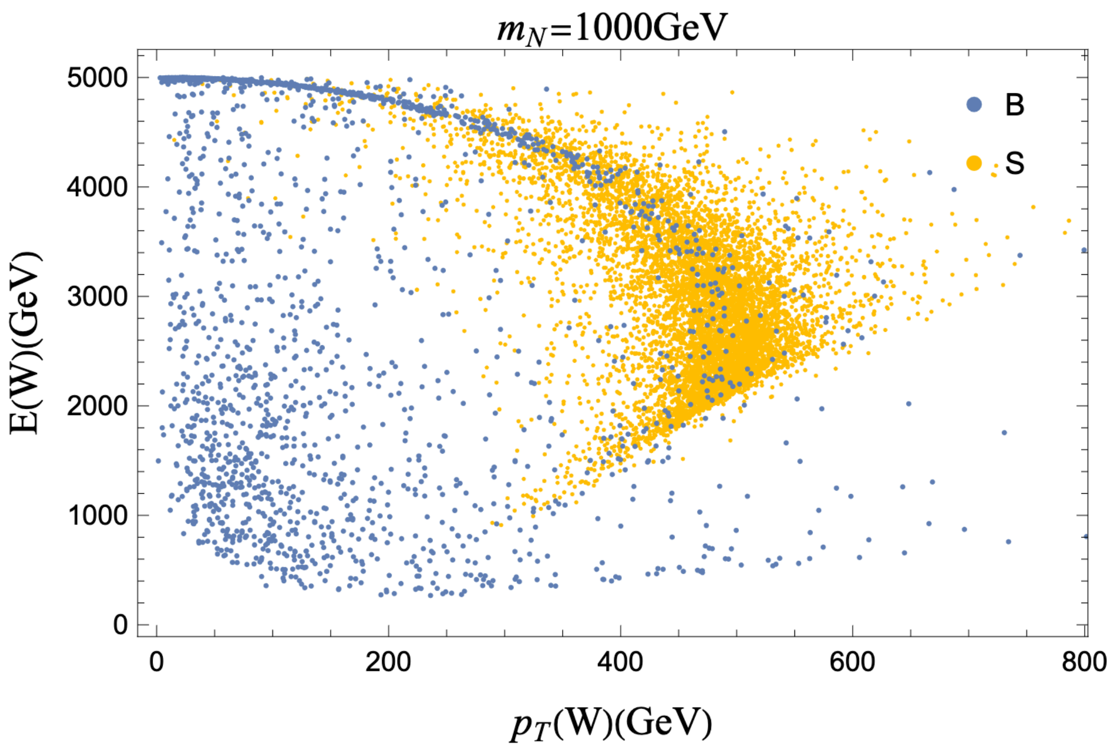


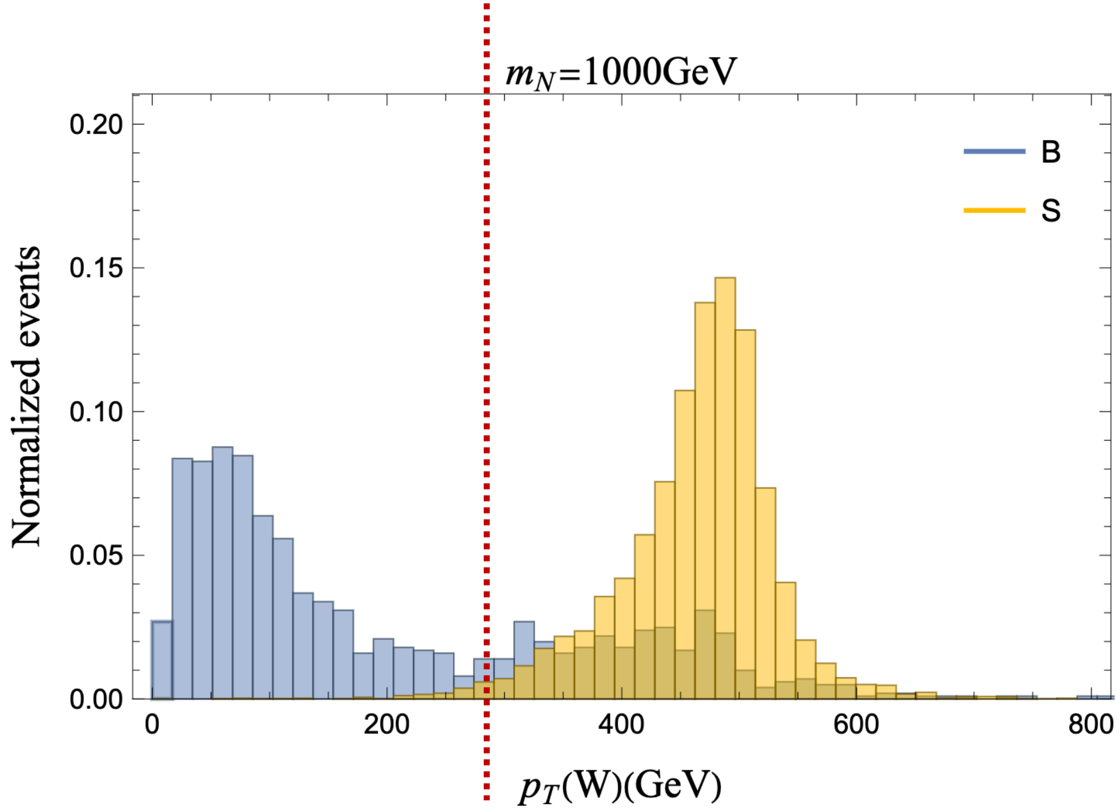
Optimization cuts I:
Missing transverse momentum needs to be less than 500 GeV.

Optimization cuts II:

For the reconstructed W boson.

1000GeV<E(W)<4950GeV which is mass window dependent

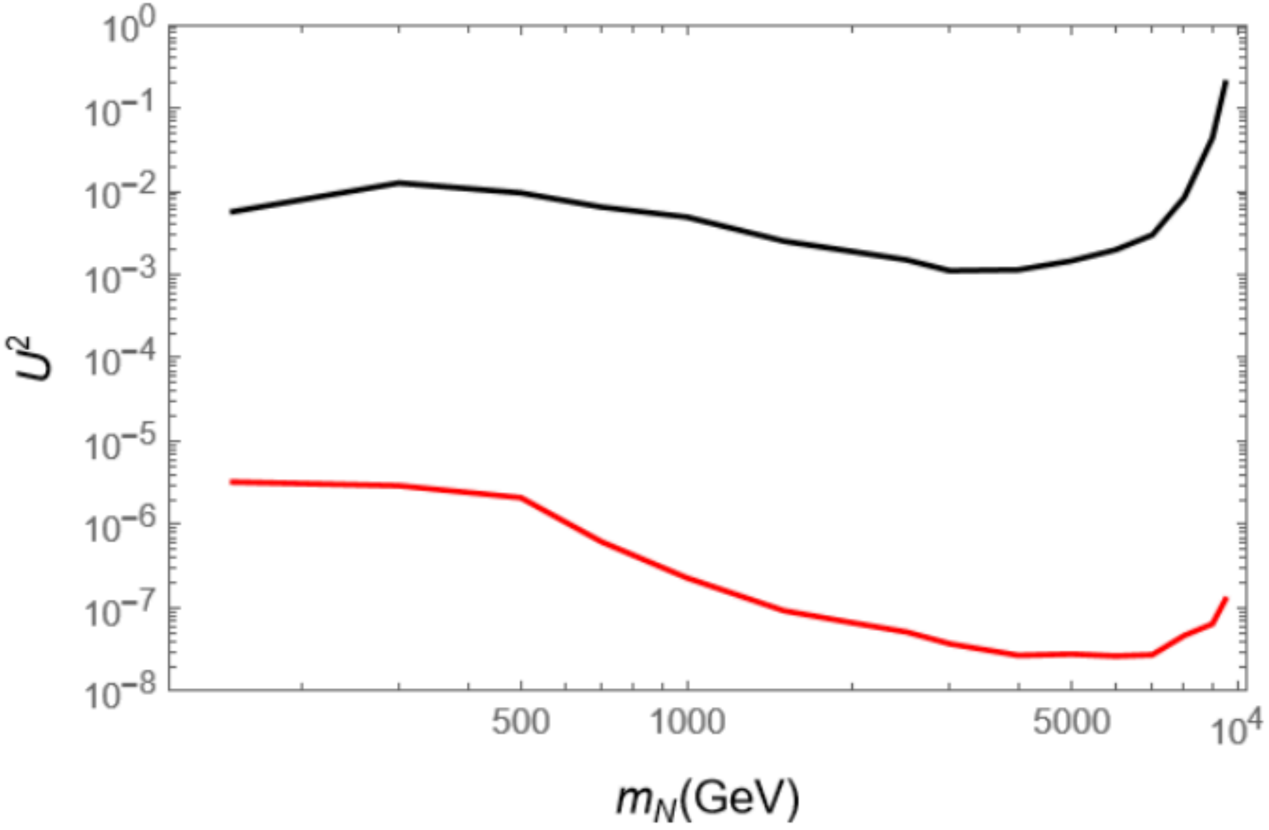




Final Results

95% exclusion bounds

10 TeV

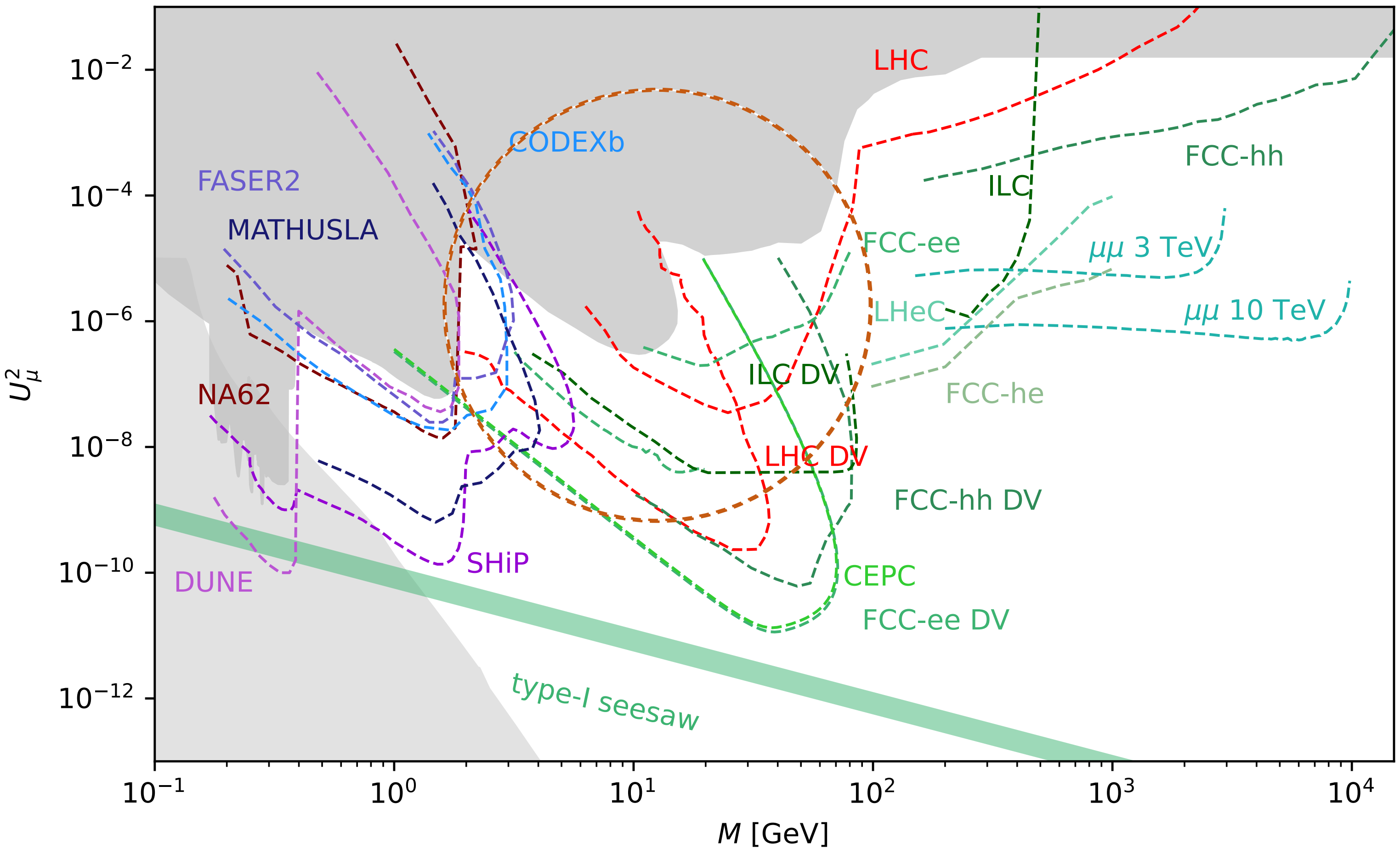


e flavor

μ flavor

Various Bounds

Next step



Short Review of Various Probes

- People have tried to constrain in the U^2-mN plane via various channels and different machines.
- Cosmo and astrophysical probe: BBN, CMB, etc
- Indirect constraints: branching ratio of SM particles decays, etc
- Direct constraints
  - Production
    - Meson decay, heavy lepton decay
    - (On-shell/Off-shell) Gauge/higgs boson decay
  - Decay
    - Short-lived
    - Long-lived

Existing Bounds

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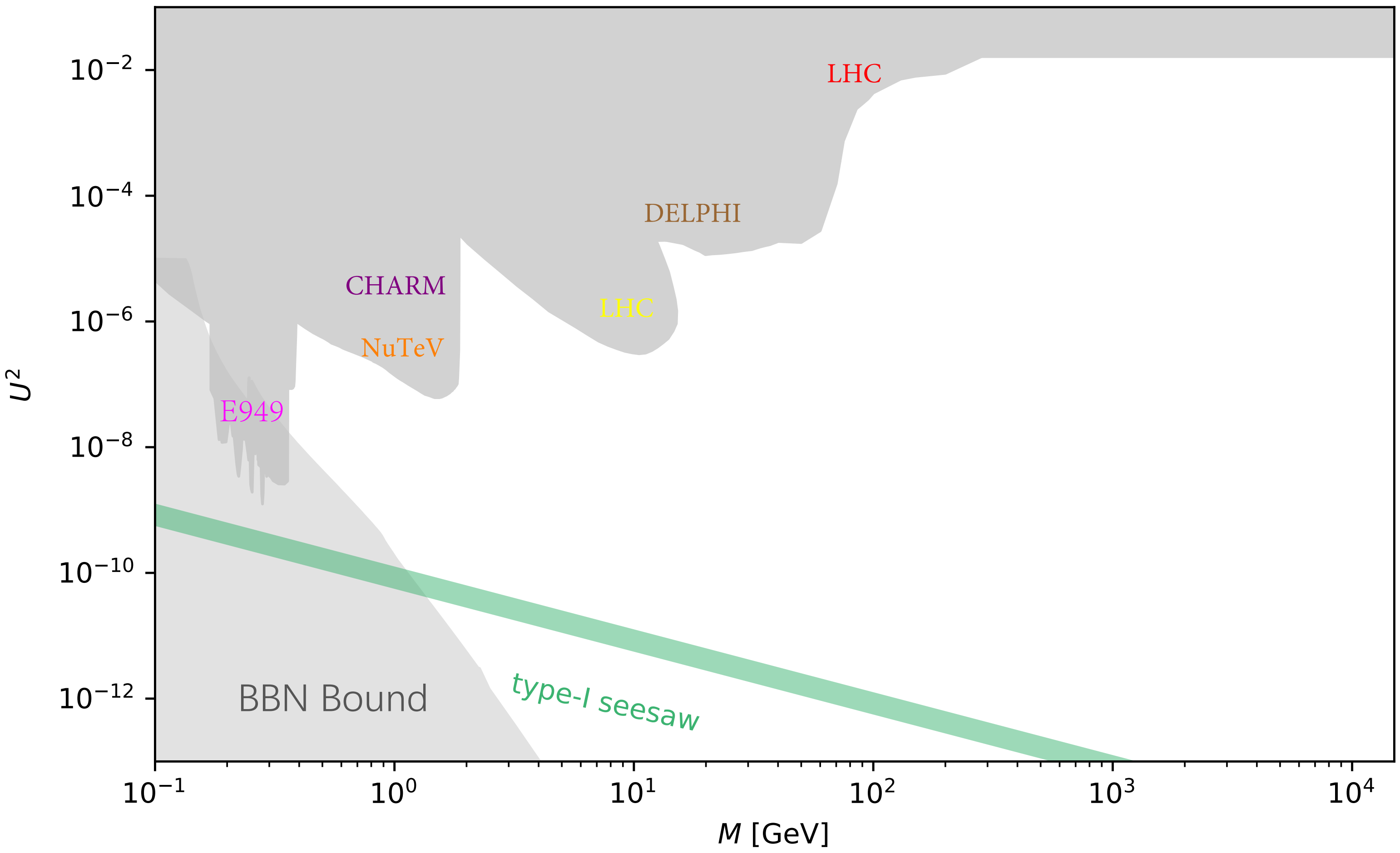
From Past Experiments



NuTeV: Drell-Yan, NHL decay

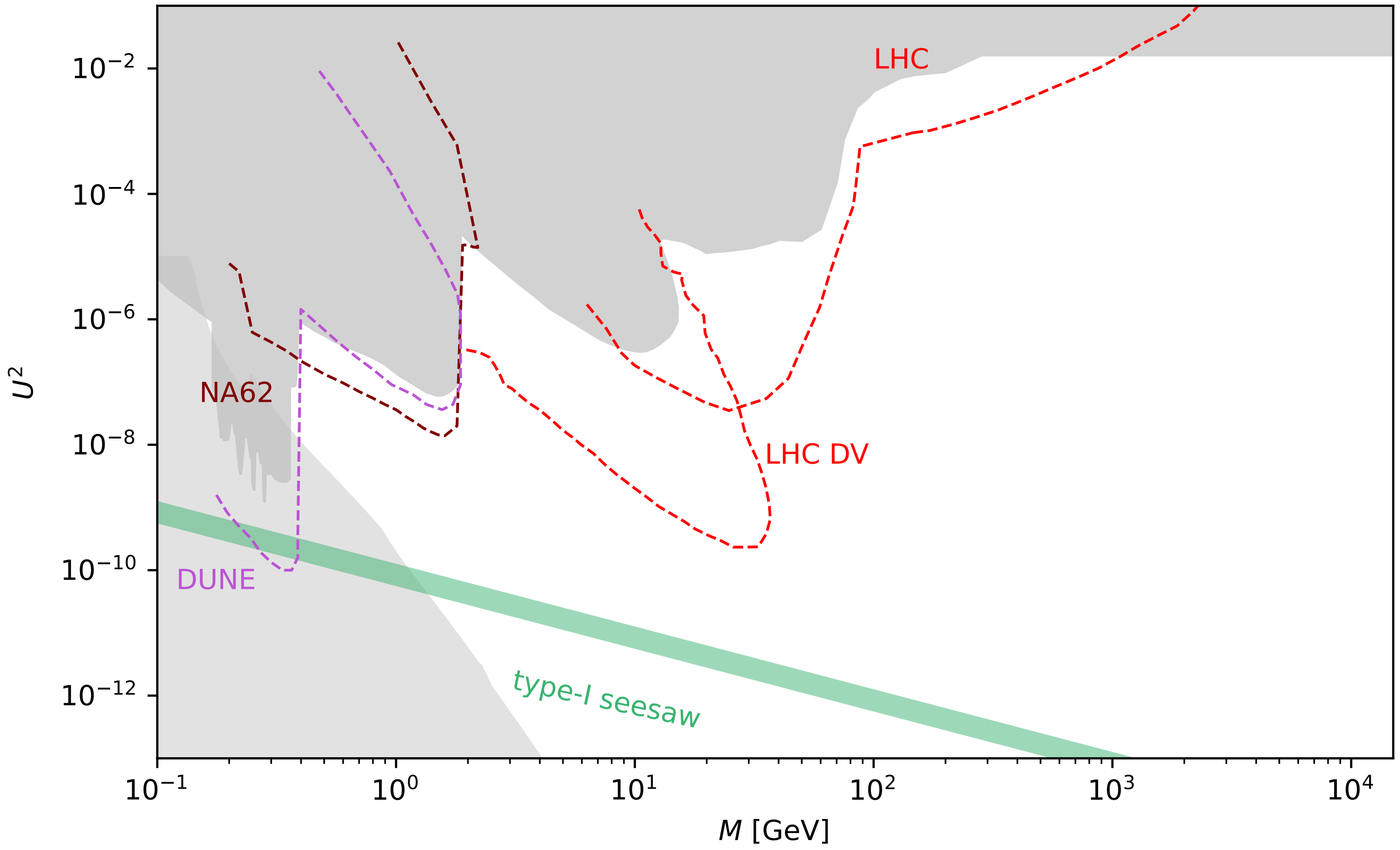
CHARM:
Beam-dump: D meson decay,
Wide-band: neutrino beam colliding with nucleus

DELPHI: Z boson decay

E949: Kaon decay

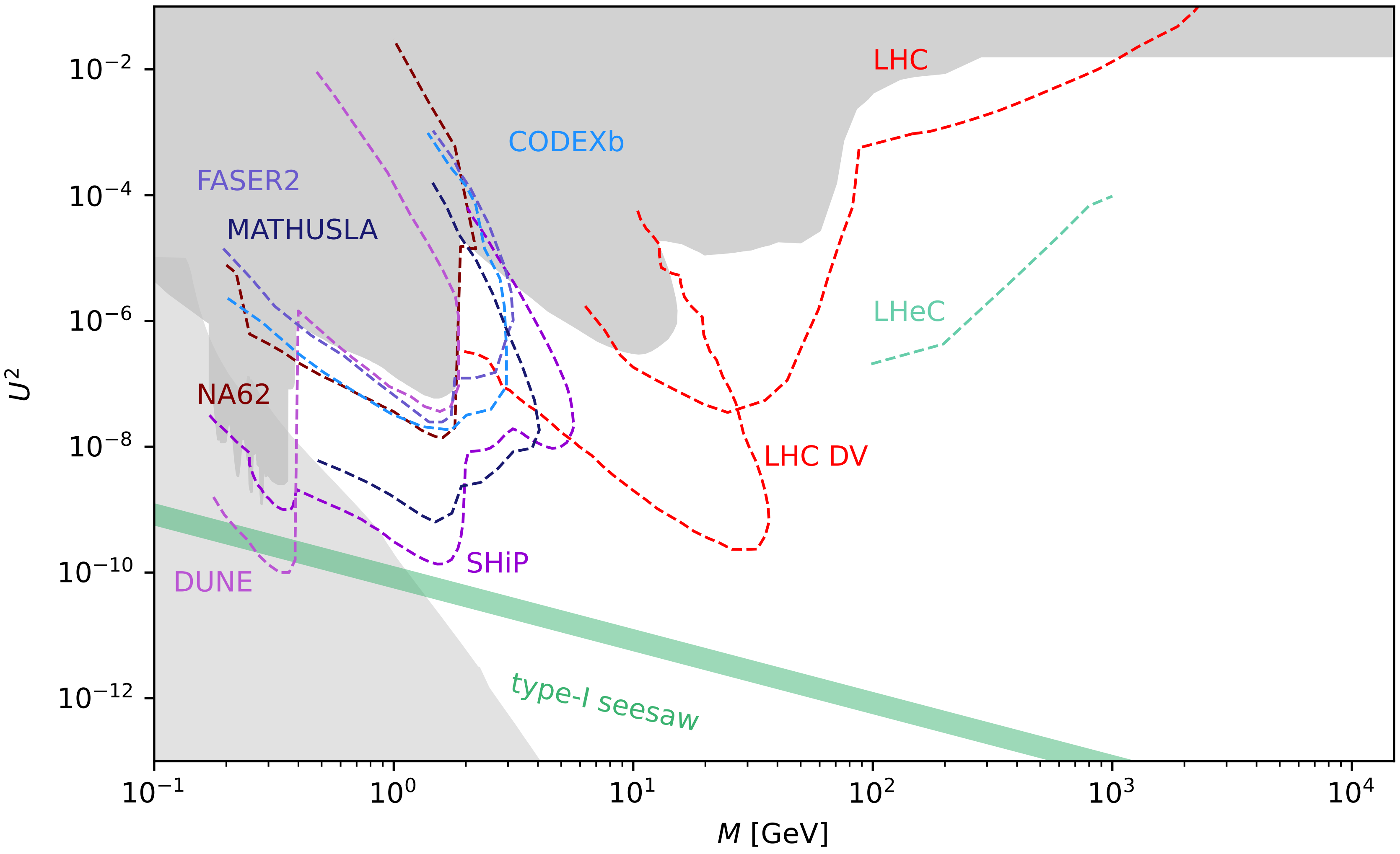
LHC: Off-shell W/Z decay

Upgraded Bounds



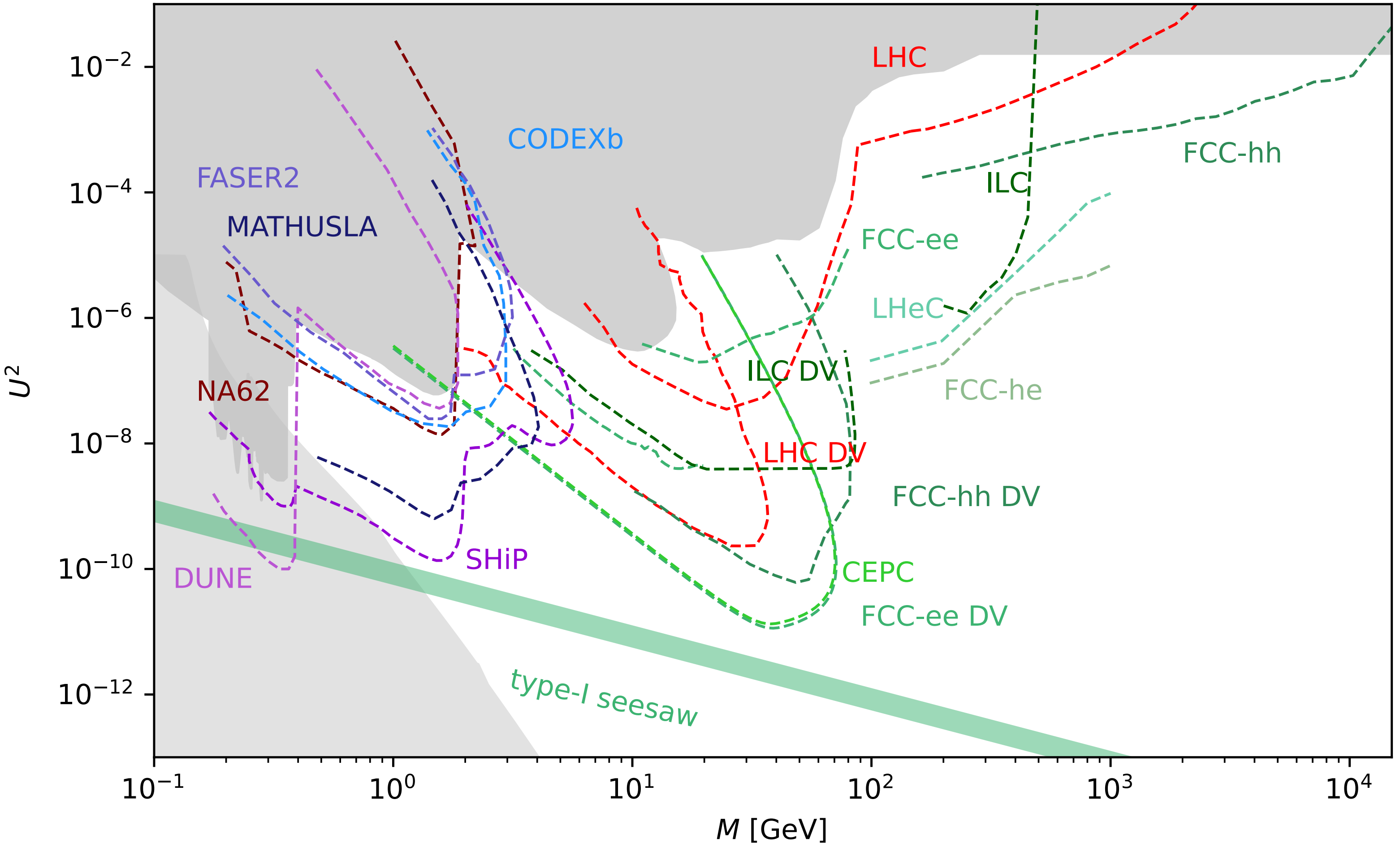
Future Upgraded Projection on LHC, NA62 and DUNE

Various Bounds



Some future proposed beam-dump experiments or far detector to probe the long-lived HNL

Various Bounds



Bounds from the proposed future collider: FCC, CEPC, ILC, LHeC

Conclusion

- Muon Collider is a good platform to probe the TeV scale HNL.
  We can open a new region in the parameter space.
- For the muon flavor case, we can probe the Umu^2 down to 10^(-6) for mN larger than O(100) GeV.
- There are t-channel singularity cases one should be careful to deal with.